

## Tilting Shear Layers in Coastal Flows

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### LONG-TERM GOALS

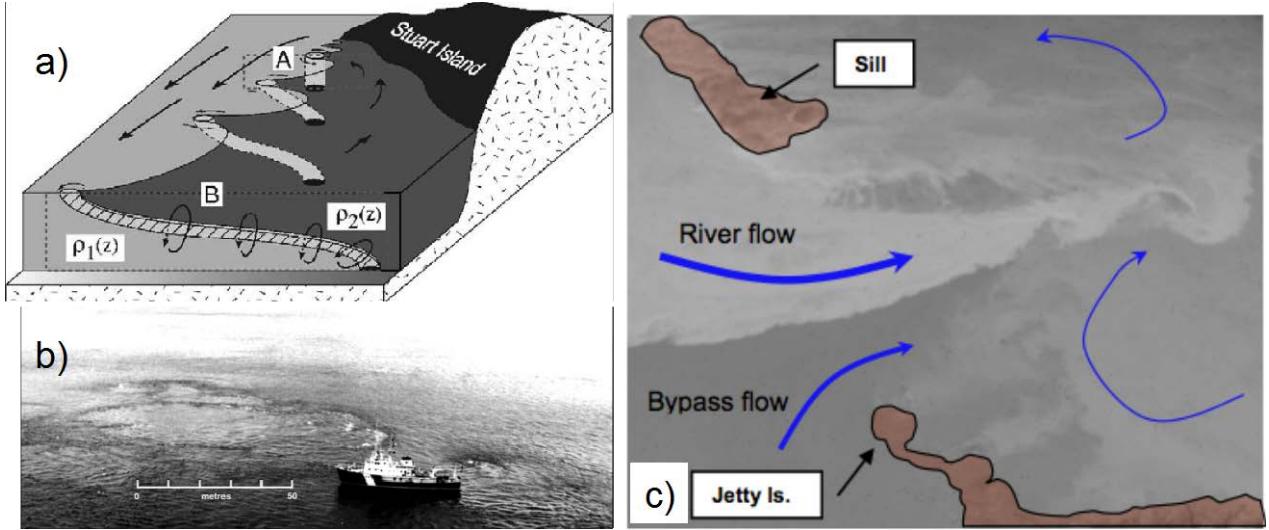
The long-term goals of this research are to explore the evolution of flows with strong horizontal shear and horizontal density gradients (see Figure 1). These “tilting” shear layers are common in strongly time-dependent coastal flows including estuarine inflows and outflows, separating flows around headlands and islands, and merging flows in morphologically complex regions such as tidal inlets, including fringing reef systems such as at Palau.

### OBJECTIVES

The specific objectives are to explore the evolution of tilting shear layer flows in coastal ocean-relevant settings, including the Haro Strait and the fringing reefs of the Palau Islands as part of the FLEAT DRI. The tilting stretches the vortices, intensifying their circulation and converting horizontal shear to vertical shear. The horizontal shear leads to the growth of vertical vortices that are subsequently tilted, stretched and intensified by the transverse gravity-driven flow. The combination of enhanced vertical shear, lateral and vertical advection of density by the tilted vortices, and subsequent breakdown of the vortices leads to the intense surface vortex expressions (the ~50m diameter boils in Figure 1b), large vertical flows, and generates strong turbulence and vertical mixing.

In particular, we want to delineate conditions for vorticity amplification, strong vertical flows, and intense mixing. We also hope, through collaboration with other FLEAT PIs, to help in understanding how these relatively small-scale flows influence the water properties within the lagoons and merge with the larger scale flows around the islands. Specific targets are: 1) degree of vertical vorticity enhancement, 2) strength of overturning flows, 3) magnitude of the turbulent diapycnal mixing and 4) the evolution of the flow downstream of the mixing zone, including mean shear and density structure.

We will expand our earlier idealized theoretical and modeling work (White and Helffrich, 2013) to include more realistic conditions of variable topography, vertical stratification in each stream, bottom drag, and rotation.



**Figure 1.** a) Sketch of tilting, horizontal shear layer near Stuart Island from Farmer et al (2002). b) Photograph of the surface expression of intense vortices near Stuart Island (from Farmer et al, 2002). c) Infra-red image of a tilting shear layer in the Snohomish River (Jessup et al, 2005).

## APPROACH

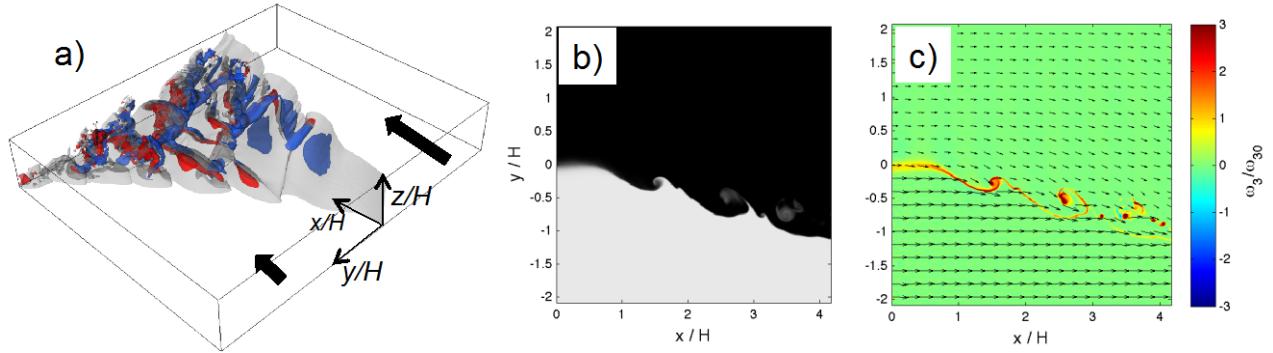
The primary approach is through numerical modeling with theoretical and scaling analysis when possible.

Two new models with DNS/LES capabilities will be used. The first is Incompact3D (Laizet and Li, 2011) which solves the three-dimensional Navier-Stokes equations using 6th-order compact finite-differences. Since high-Reynolds number DNS of spatially evolving tilting shears will likely be prohibitive, we have added dynamic-Smagorinsky LES capabilities to Incompact3D.

We will use Incompact3D for our initial idealized studies. For topographically-complex flows in more realistic setting, we plan to use the new Stratified Ocean Model with Adaptive Refinement (SOMAR). This code has been developed by E. Santilli and A. Scotti at UNC Chapel Hill and is specifically intended for modeling turbulence and internal waves in ocean environments with complex topography, vertical stratification, nonhydrostatic effects, and potentially large horizontal to vertical aspect ratios. The code solves the three-dimensional Boussinesq equations using the finite-volume Piecewise Parabolic Method and a novel Poisson solver that permits large grid aspect ratios. In addition, the code handles multi-level adaptive grid refinement. An LES scheme is under development, which will allow modeling of large Reynolds number turbulent flows. This code should be ideal for incorporating topography from specific field sites, e.g. around Palau or other coastal regions, for comparison with observations.

## WORK COMPLETED

At this stage the effort has just been initiated. The immediate focus is on two idealized problems designed to explore, individually at first, the roles of ambient vertical stratification and rotation on the evolution of tilting shear layers. In the absence of either rotation or vertical stratification previous work (Helffrich and White, 2013) has identified the parameter



**Figure 2. Numerical solution of a tilting shear layer with the denser, faster stream entering at  $x=0$  for  $y<0$ .** a) Perspective view of the mid-density surface (gray) and regions of large vertical velocity (red-up, blue-down). b) Top view of near-surface ( $z/H = 0.97$ ) density field (white-denser, black-lighter). c) Near-surface vertical vorticity (colors) and velocity vectors.

$$\gamma = 5 \frac{l_u}{H} \frac{(g'H)^{1/2}}{|\Delta U|}.$$

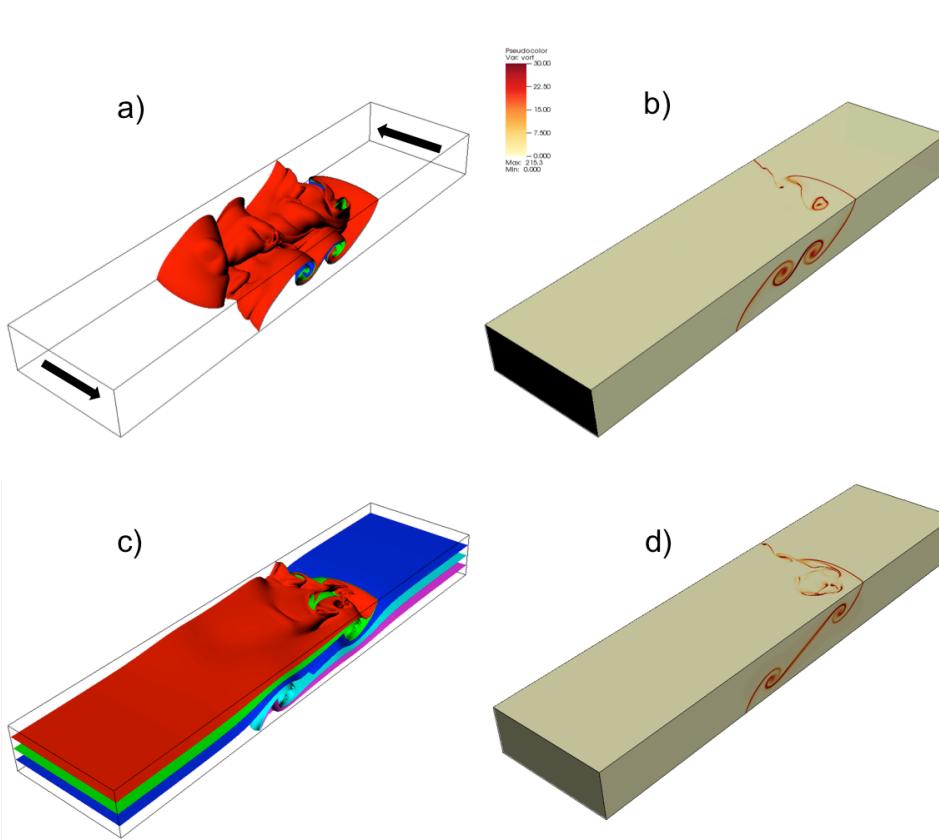
Here  $l_u$  is the horizontal width scale of the shear layer,  $H$  is the water depth,  $g'$  is the reduced gravity based on the lateral density contrast between the two streams, and  $|\Delta U|$  is the velocity difference between the two streams. The parameter  $\gamma$  is the ratio of the timescale of growth of the primary shear instability to the time for a gravity current with speed  $c_f = (g'H)^{1/2}/2$  to move a distance equal to  $H$ . For  $\gamma \ll 1$  shear instability dominates the evolution with only weak effects from tilting and for  $\gamma \gg 1$  gravitation slumping dominates and suppresses the shear instability. For intermediate values, the shear instability evolves on the same timescale as the gravitational tilting and the interaction is strong with vertical Rayleigh vortices interacting with emerging Kelvin-Helmholtz roles. Figure 2 shows a numerical calculation of a spatially evolving shear layer for  $\gamma = 0.29$  that illustrates these features.

The newly initiated extensions involving ambient stratification and rotation. The ambient vertical stratification introduces a new parameter,  $\Delta\rho_{vert}/\Delta\rho$ , the ratio of the vertical density difference to the horizontal difference. Rotation introduces the Rossby number,  $Ro = \Delta U/f l_u$ , the ratio of the ambient vertical vorticity to the planetary vorticity. Here  $f$  is the Coriolis frequency. In this case the sign of  $Ro$  is an important consideration as anticyclonic rotation ( $Ro < 0$ ) introduces an inertial instability of the primary vertical vortices in the absence of stratification (Potybitsin and Peltier, 1998).

The ongoing effort is centered on DNS calculations with modest Reynolds numbers  $Re = O(10^4)$ . Additionally they examine the temporal development of the flows in a periodic channel with length equal to one wavelength of the primary shear instability. This facilitates a more rapid exploration of parameter space before moving on to the more realistic spatially evolving shear layer shown in figure 2.

## RESULTS

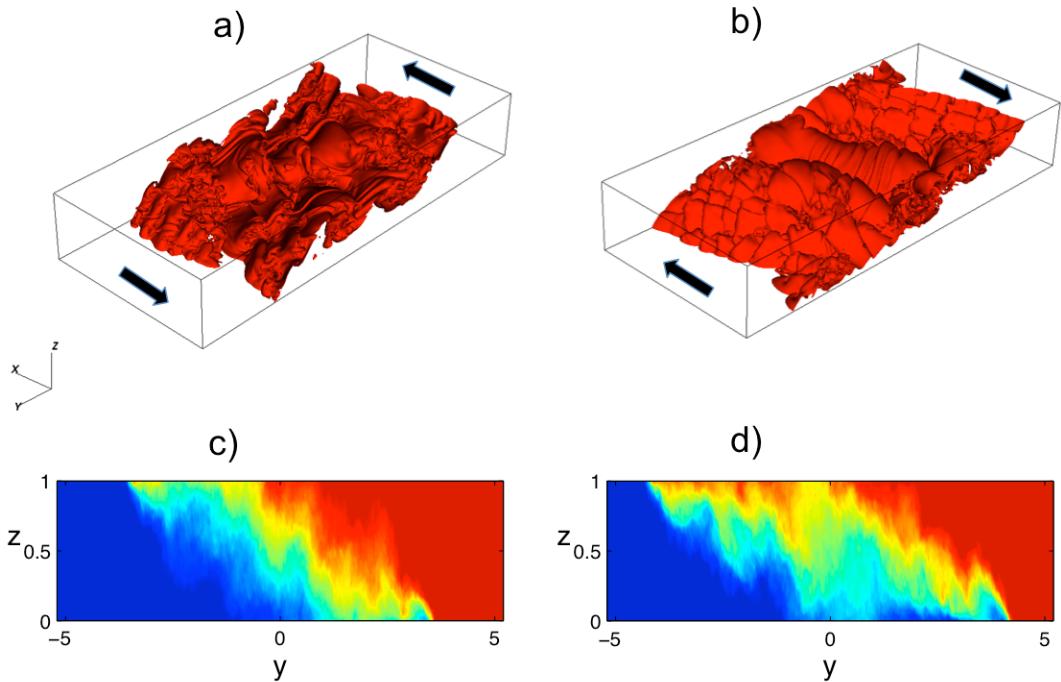
Some example results on the effect of ambient vertical stratification are presented in Figure 3. Figure 3a shows a perspective view of iso-surfaces of density for a DNS calculation ( $Re = 4000$ ) with  $\Delta\rho_{vert}/\Delta\rho = 0$  and  $\gamma = 0.42$  at a point in the evolution where the tilted primary vortex and developing Kelvin-Helmholtz billows are beginning to interact strongly. The magnitude of the vorticity



**Figure 3: Effect of ambient vertical stratification. Perspective views of (a) density iso-surfaces and (b) magnitude of the vorticity,  $|\omega|$ , for  $\gamma = 0.42$  and  $\Delta\rho_{vert}/\Delta\rho = 0$ . (c) and (d) show the same for  $\gamma = 0.42$  and  $\Delta\rho_{vert}/\Delta\rho = 2$ . Both cases are shown at the same time.**

qvector,  $|\omega|$ , is shown in Figure 3b. The intensification of vorticity in the surface front and coherent core of the primary vortex are clear. The stretching has resulted in vorticities of more than ten times the maximum vorticity in the initial  $tanh$  shear layer. Similar plots for a case with the same  $\gamma = 0.42$  and ambient vertical stratification  $\Delta\rho_{vert}/\Delta\rho = 2$  are shown in Figures 3c and d. The ambient vertical stratification has resulted in a weakened primary vertical vortex and a change in the location of the Kelvin-Helmholtz billows. The front positions are almost the same in the two cases (both shown at the same time). What is markedly different is the vertical mixing as measured by the increase of the background (resorted) potential energy increases from the initial state. In this example the ambient vertical stratification leads to an increase of about 50% in the irreversible mixing above the vertically unstratified base case. A maximum increase of more than 70% occurs for  $\Delta\rho_{vert}/\Delta\rho \approx 1$ , indicating that there are optimal conditions for mixing. A detailed analysis of the dynamics and energetics over the range of relevant parameters is underway.

The effects of rotation are illustrated in Figure 3 where the mid-density iso-surface at  $t = 4$  is shown for two runs in an  $x$ -periodic domain with initial flow with  $\gamma = 0.42$  and  $Ro = 119$ . The values of  $\gamma$  and  $Ro$  are consistent with the Haro Strait observations near the separation point, Section A, in Figure 1. In Figure 3a the initial barotropic vorticity,  $-u_y$ , has the same sign as  $f$ . The primary tilted vortex is present and the subsequent evolution is similar to the non-rotating case. However, when the initial barotropic vorticity has the opposite sign as  $f$ , Figure 3b, the primary vertical vortex has been eliminated. Perhaps surprisingly, this leads to slightly greater vertical mixing and slightly faster lateral propagation of the gravity current fronts as shown in Figures 3c and d, where the corresponding  $x$ -averaged density fields are shown.



**Figure 4: Tilting shear layers in the presence of rotation for  $\gamma = 0.42$  and  $Ro = 119$ . Isosurfaces of the mid-density at  $t = 4$  for a) initial barotropic vorticity with the same sign as  $f$  ( $Ro = 119$ ) and b) initial barotropic vorticity with the opposite sign as  $f$  ( $Ro = -119$ ). Panels c) and c) show the  $x$ -averaged density fields for a) and b), respectively.**

## IMPACT/APPLICATIONS

While still preliminary and exploratory, the numerical calculations should improve our understanding of the evolution of tilting shear layers in parameter regimes relevant to the coastal oceans (depths  $H = O(10\text{-}100\text{m})$  and horizontal length scales  $O(10^3 \text{ - } 10^4\text{m})$ ).

An intended impact is for this work to give guidance to the planning and execution of the FLEAT DRI observational effort and the subsequent analysis the observations. At the FLEAT planning meeting at Scripps in June 2015 the scope of the overall modeling effort was discussed and placed into context. The scales we focus on are among the smallest of the overall FLEAT modeling effort, but connect very

well to the larger scale efforts focused on island wakes, submesoscale processes, eddies, fronts, and lee waves. We will continue working with the larger-scale modelers and observational efforts to help interpret the physical processes of interest to the project.

## **TRANSITIONS**

None

## **RELATED PROJECTS**

None

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## **PUBLICATIONS**

None

## **PATENTS**

None

## **HONORS/AWARDS/PRIZES**

None